Development of finger force coordination in children

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COORDINATION

- What is motor coordination?
- Motor coordination is when several parts of a movement or several body parts work together
- What does it mean for several parts to work together?

COORDINATION

- Children are an ideal population for studying coordination (or lack thereof)
- By looking at a range of ages, we can see how different types of coordination develop

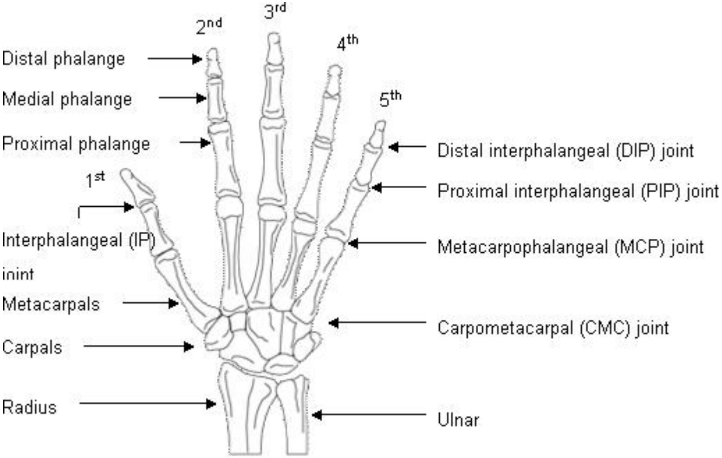
Redundancy in grasping

- Redundancy = more solutions than necessary
- When grasping, we are required to solve (at least) these mostly redundant problems:
    - Select grasp points for a particular task
    - Select the posture of the hand
    - Select the stiffness properties of the fingers and grasp
    - Coordinate the grip and tangential forces of the fingers
    - Share the force produced by multiple fingers
- and ideally do this in an efficient / optimal way

Degrees of freedom problem

There are many degrees of freedom in the hand

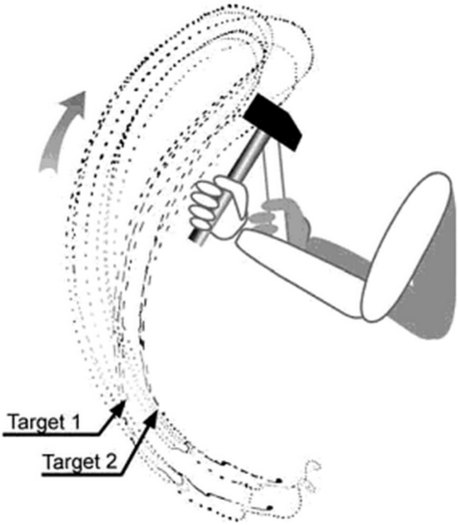
>20 joints



Large number of muscles

DEGREES OF FREEDOM PROBLEM

Repetition without repetition

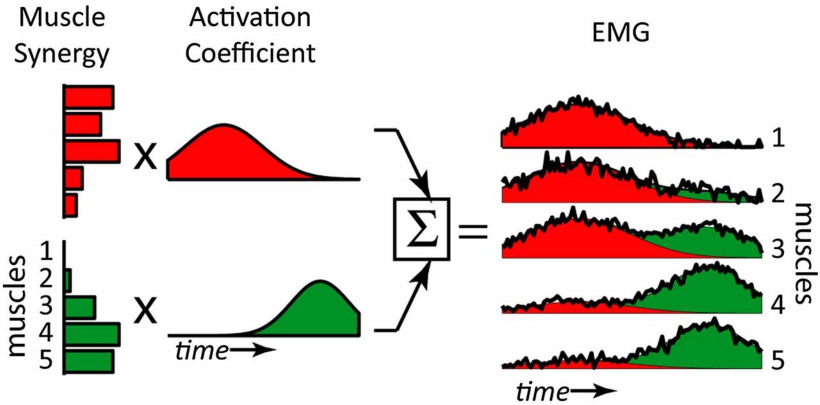


What is a synergy

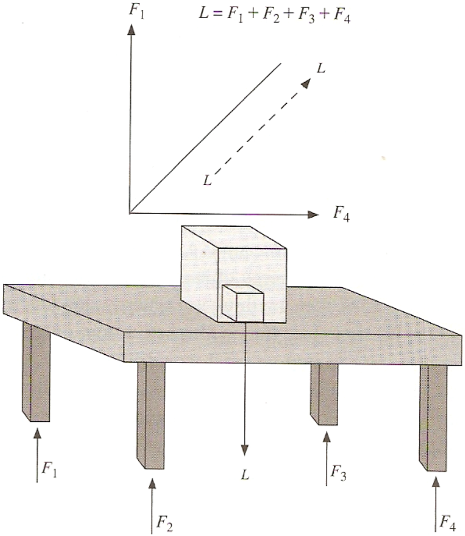
- Usual definition of a synergy = two or more things working together, to produce more than they could alone

What is a synergy

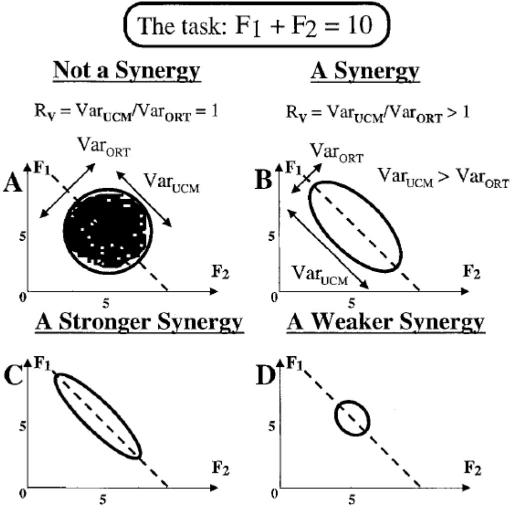
- Muscle synergies = pattern of muscle coactivation recruited by a single neural command



IS A TABLE A SYNERGY?



Uncontrolled Manifold (UCM)



Prehension synergies

A *prehension synergy*

- is a combined change of finger forces and moments during multi-finger prehension tasks
- adjusts to changes in task parameters
- compensates for external or self-inflicted disturbances

UNCONTROLLED MANIFOLD (UCM)

- The *uncontrolled manifold* approach (Scholz and Schöner, 1999) can be used to explain the variance observed when a given task has more degrees of freedom than necessary.
- We calculate which changes from the average (mean) performance that do not affect the goal of the task.
- Then the variance that does not change the performance variable (V_{UCM} - "good" variance) and variance that does change the performance variable ($V_{ORT} -$ "*bad*"*variance*) can be calculated.

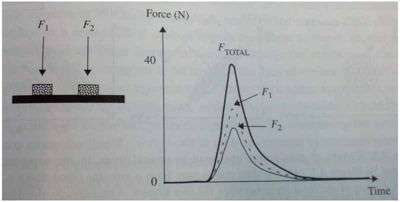
Calculation of the good and bad variance

- Consider a task where the subject has to control the total force, which is the sum of the force produced by two fingers.

$$dF_{TOT} = \begin{bmatrix} 1 & 1 \end{bmatrix} d\mathbf{f}$$

where

$$d\mathbf{f} = \begin{bmatrix} df_i \\ df_m \end{bmatrix}$$



Calculation of the good and bad variance

- We now consider combinations of force produced by the fingers that do alter the total force, i.e.

$$0 = \begin{bmatrix} 1 & 1 \end{bmatrix} \mathbf{e_i}$$

- This is the null space of this transformation.
- For two fingers, this is:

$$\begin{bmatrix} -1 \\ 1 \end{bmatrix}$$

- i.e. When the changes in one finger cancel out the changes in the other fingers
- When there are more fingers, the changes are more complicated

Calculation of the good and bad variance

- We project the mean-free modes onto these directions, and sum them to find the *good* variance

$$f_{||} = \sum_{i=1}^{n-p} \left(\mathbf{e_i}^T \cdot d\mathbf{f} \right) \mathbf{e_i}$$

Calculation of the good and bad variance

- To calculate the *good* variance, V_{UCM}, we calculate the amount of this variance per degree-of-freedom (DOF)

$$V_{\mathrm{UCM}} = \frac{\sum |f_{||}|^2}{(n-p)\, N_{\mathrm{trials}}}$$

- The bad variance is calculated in a similar way:

$$f_{\perp} = d\mathbf{m} - f_{||}$$

$$V_{\mathrm{ORT}} = \frac{\sum |f_{\perp}|^2}{p N_{\mathrm{trials}}}$$

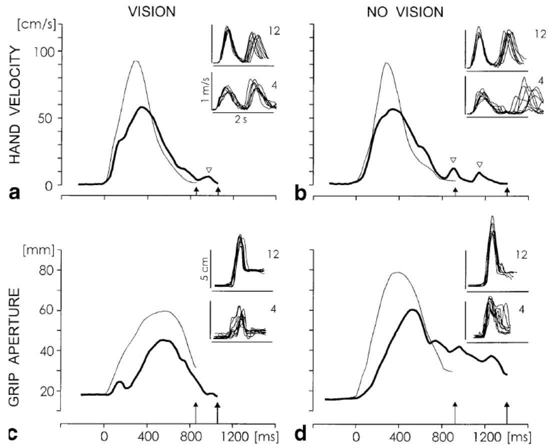
CALCULATION OF THE GOOD AND BAD VARIANCE

- By comparing the relative size of the good and bad variance, we can determine whether the fingers are acting as a *synergy*
- *good variance* $>$ *bad variance*: the fingers are correcting each other, so we call this a synergy
- *good variance* $\approx$ *bad variance*: we do not see a synergy - the fingers are acting independently
- *bad variance* $>$ *good variance*: destabilizing synergy - the fingers are producing highly correlated movement, so errors are amplified

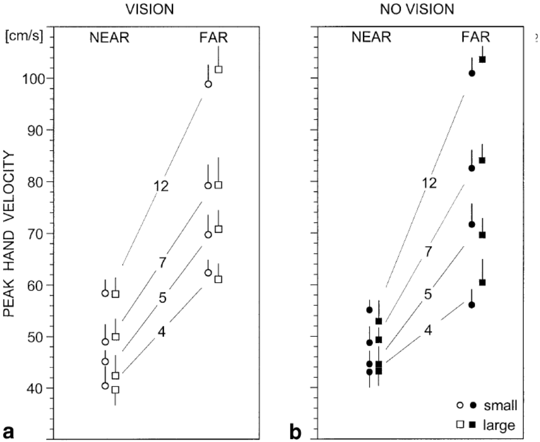
Reach to grasp coordination

- The reach-to-grasp movement essentially has two components:
  - Transport component - bring the arm to the right place
  - Grasp component - shape the fingers in preparation for grasping the object
- Coordination of these two components is observed in adults and develops throughout childhood, as quantified by arm velocity (transport) and grip aperture (grasp)

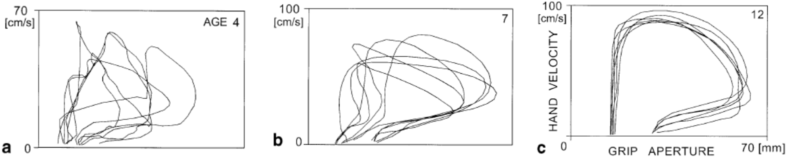
Reach to grasp coordination



Kuhtz-Buschbeck et al. (1998)


VISION
NO VISION
[cm/s]
NEAR
FAR
PEAK HAND VELOCITY
100
90
80
70
60
50
40
12
7
5
4
a
b
small
large

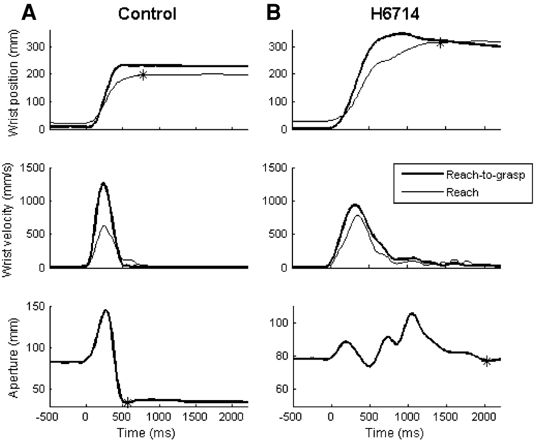
Reach to grasp coordination



- With development, we observe
  - a stereotypical pattern of coordination of hand velocity and grip aperture
  - a reduction in variation

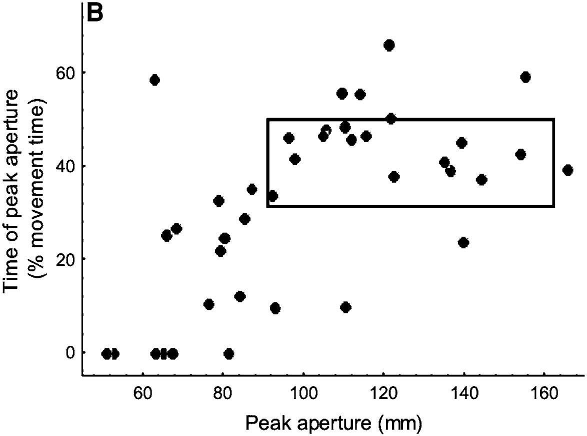
ACUTE HEMIPARETIC STROKE PATIENTS

LANG ET AL., 2005

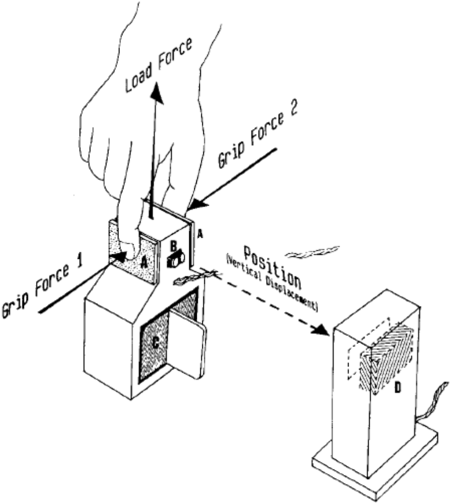


Acute hemiparetic stroke patients

Lang et al., 2005

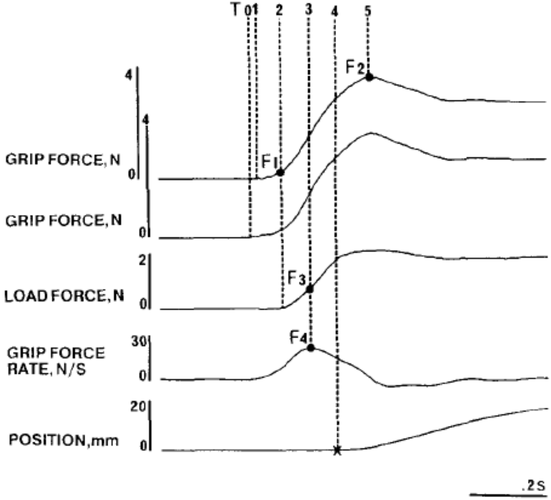


GRIP FORCE-LOAD FORCE COORDINATION

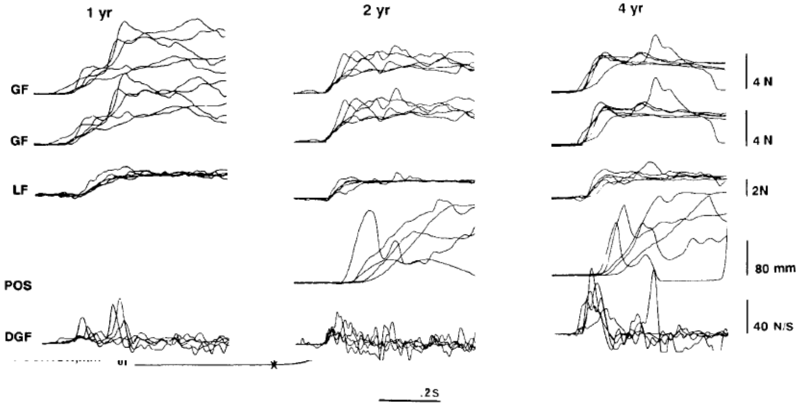


Forssberg et al., Exp. Br. Res, 1991

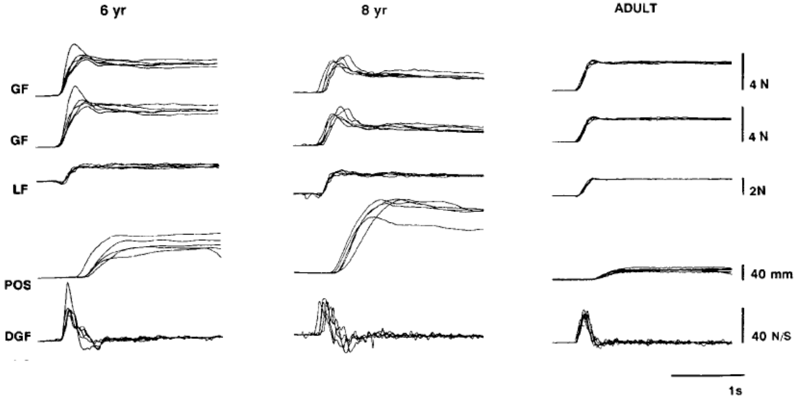
GRIP FORCE-LOAD FORCE COORDINATION



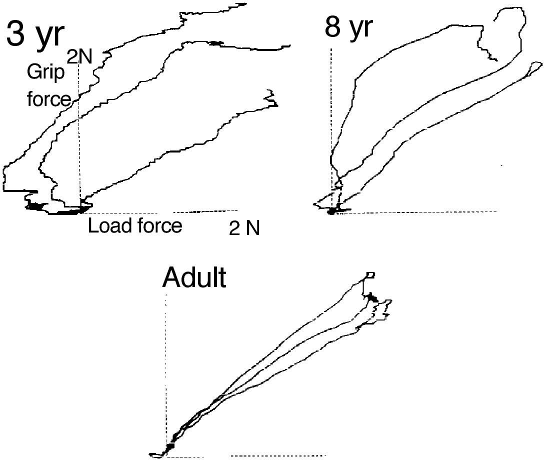
Grip force-load force coordination



Grip force-load force coordination



Grip force-load force coordination

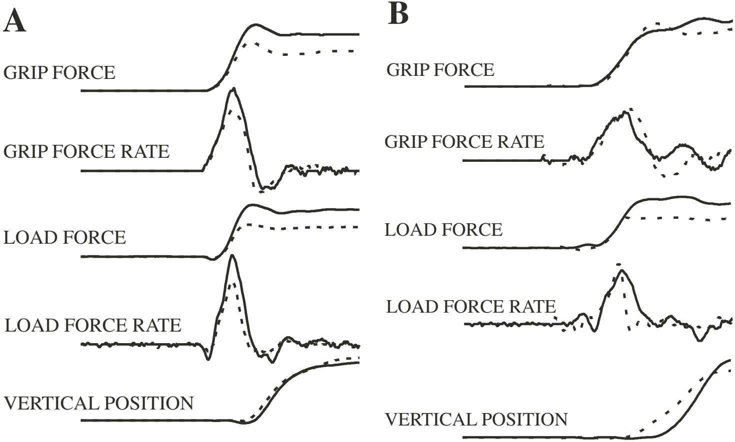


Grip force-load force coordination

- Adult grasping is characterized by coordinated load and grip force
- Grip force and load force start at approximately the same time
- There is a single peak in the grip force rate, suggesting a good prediction of the forces needed
- These stereotypical properties develop over childhood

Hemiparetic stroke patients

Raghavan et al., 2006



Coordination of finger force sharing

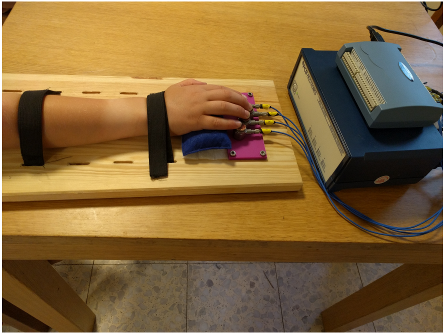
- While the development of reach-to-grasp kinematic coordination, and grip-force / load-force coordination are well understood, the development of force coordination is not well understood
- Very few studies have been performed in children using the UCM, and there have not been any studies looking at the development of the UCM in children
- In this study, we aim to track the development of finger force synergies in children, and test whether it predicts motor ability from standard tests

EXPERIMENT

- We measured finger force coordination in children
- This is part of a larger project comparing typically developing children with children with developmental and acquired brain injury
- We tested 60 children aged between 4 and 12

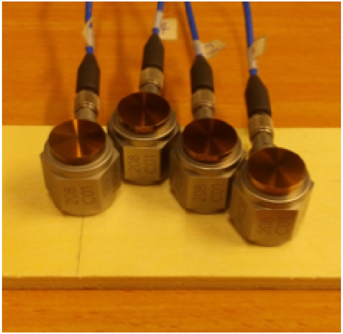
Experiment - the task

- In the experiment, we measured the finger force from the four fingers (not the thumb)
- The setup is designed to only measure forces from the fingers



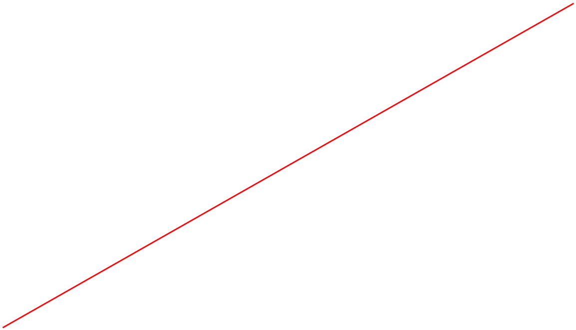
Experiment - the task

- We measured the forces using four unidimensional piezoelectric force sensors (PCB 208C01)



Experiment - the task

- Typically we use force ramps in these experiments
- The cursor moves from left to right at a fixed rate
- The height is proportional to the force produced



EXPERIMENT - THE TASK

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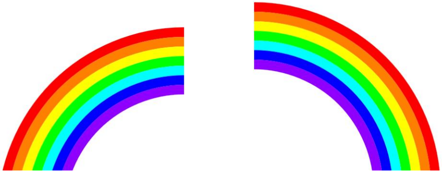


EXPERIMENT - THE TASK

- For each subject, we initially measured the maximal voluntary contraction (MVC), 3 times
- This allows us to normalize the task for each subject
- We set the top of the screen to equal 25% of the MVC
- In this way, we make the task equally difficult across subjects, and prevent fatigue

EXPERIMENT - INCLUSION CRITERIA

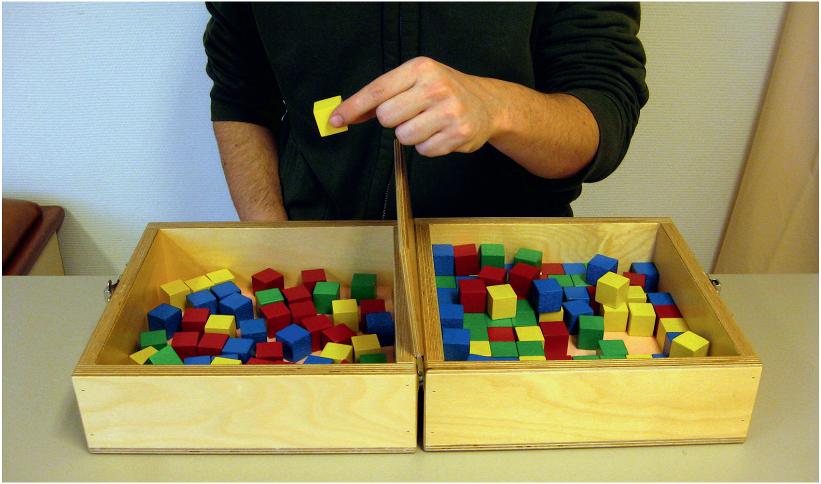
- Age 4-12
- Male and female children
- Able to understand instructions
- Child and parent / guardian gave consent

Experiment - exclusion criteria

- Illness or injury that causes weakness
- Known orthopedic or neurological problems
- Uncorrected vision problems
- Development, cognitive or language impairment

Experiment - Other measurements

- Box and blocks - both hands



EXPERIMENT - OTHER MEASURES

- Jebsen-Taylor: 6 parts (without writing) - both hands

EXPERIMENT - JEBSEN TAYLOR

- Turning over 3 inch * 5 inch cards (7.6 cm * 12.7 cm)
- Picking up small common objects (paper clip, bottle cap, coin)
- Simulated feeding using spoon and five kidney beans
- stacking checkers
- picking up large light objects (empty tin can)
- picking up large heavy objects (full tin can)

EXPERIMENT - OTHER MEASURES

- Conners (ADHD)

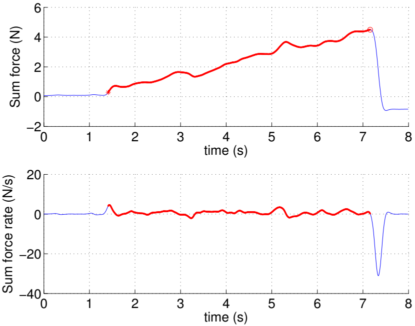
Please mark the appropriate box with an 'X'

	A	B	C	D
Observation	Not at all	A little	Pretty much	Very much
1. Sits fiddling with objects				
2. Hums and makes other noises				
3. Falls apart under stress/examination				
4. Co-ordination poor				
5. Restless and overactive				
6. Excitable				
7. Inattentive				
8. Difficulty in concentrating				
9. Over sensitive				
10. Overly serious or sad				
11. Daydreams				
12. Sullen or sulky				

Analysis

- We applied a fourth order two-way lowpass Butterworth filter at 4 Hz
- We did not use the first two repetitions (as subjects were learning the task)

Analysis

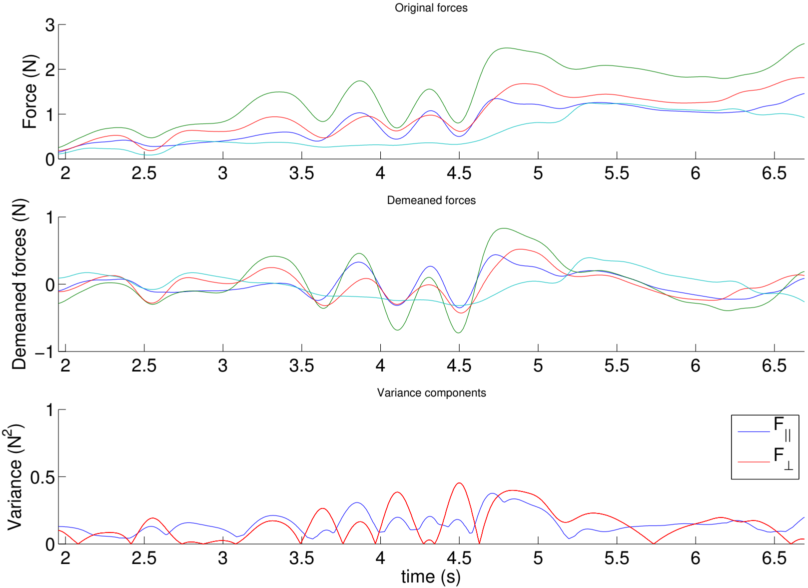


- To identify movement initiation, we start at 50% of peak force, and go backwards until we reach 5% of peak force
- The drop-off of force at the end of the movement is found by checking if there is a large negative peak in the last 20% of the movement - if so, we go backwards to find the force-rate zero crossing (force peak)

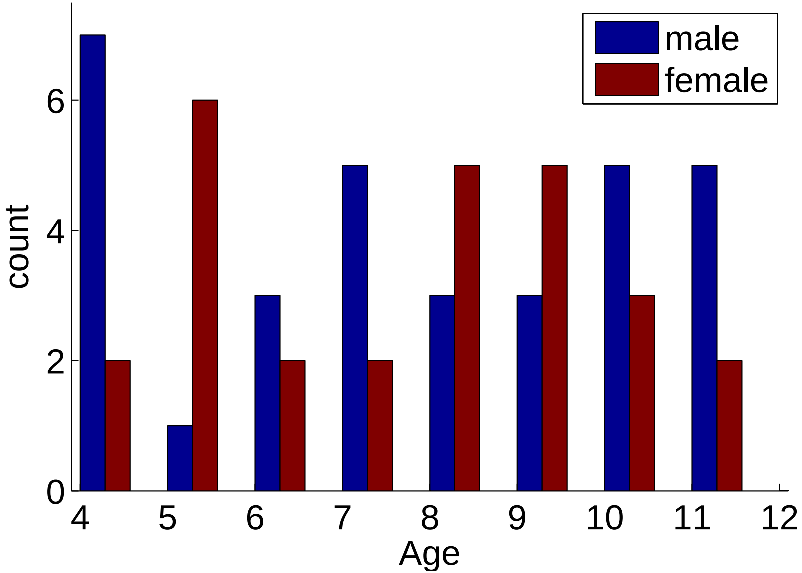
Analysis - Single trial UCM

- UCM usually calculates the variance across multiple trials
- However, with children, the performance (and probably strategy) varies a lot across trials, and it would be difficult to get them to perform so many repetitions
- Instead, we perform single trial UCM
- We de-mean each of the forces to compare the fluctuations between fingers

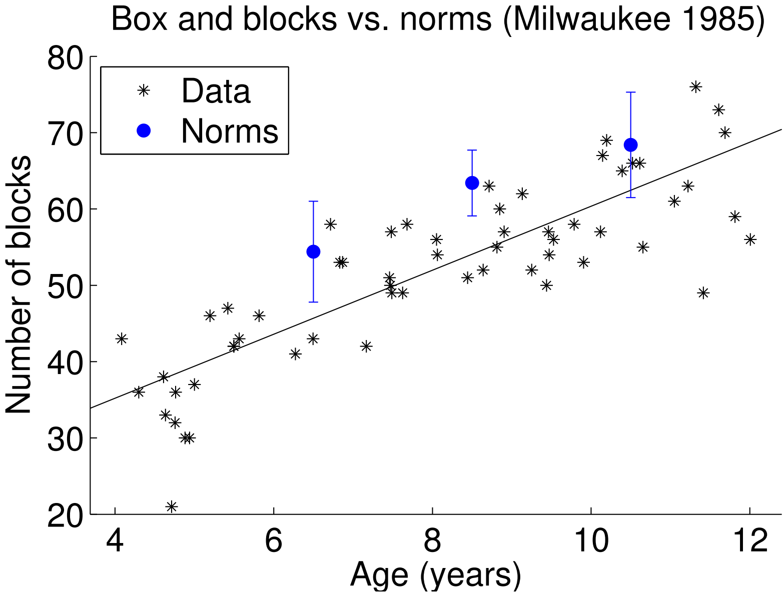
Analysis - Single trial UCM



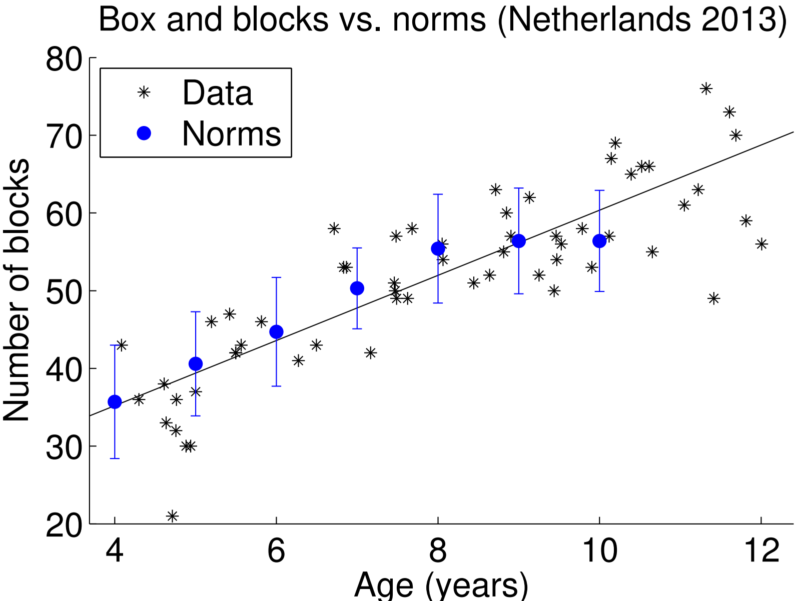
Experiment - results (demographics)



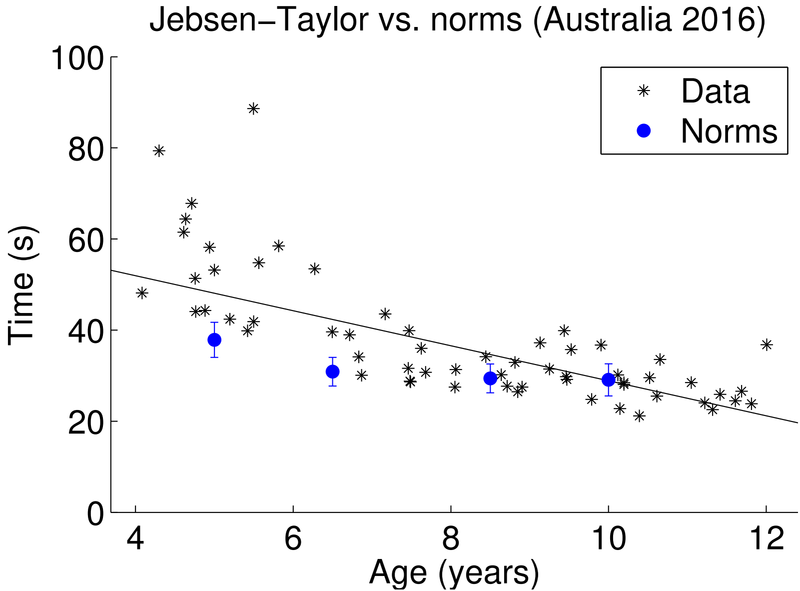
Experiment - results (Box and blocks)



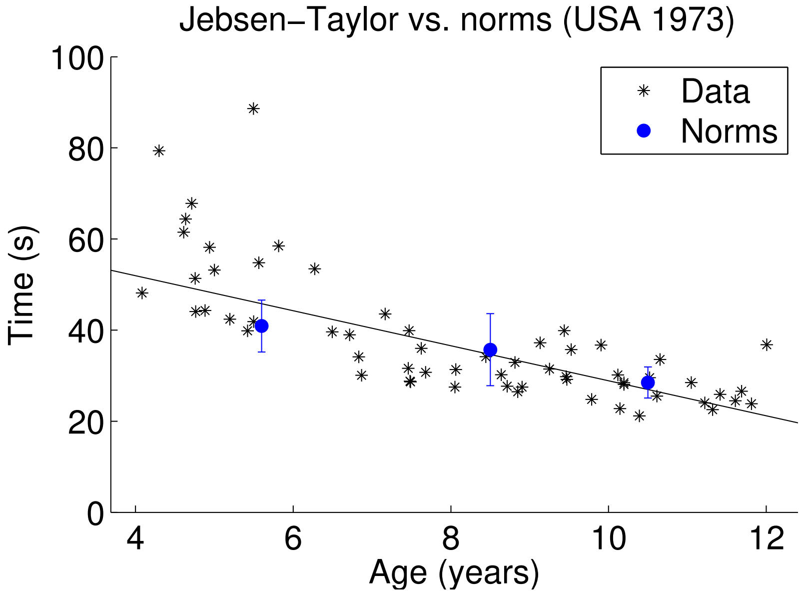
Experiment - results (Box and blocks)



Experiment - results (Jebsen-Taylor)

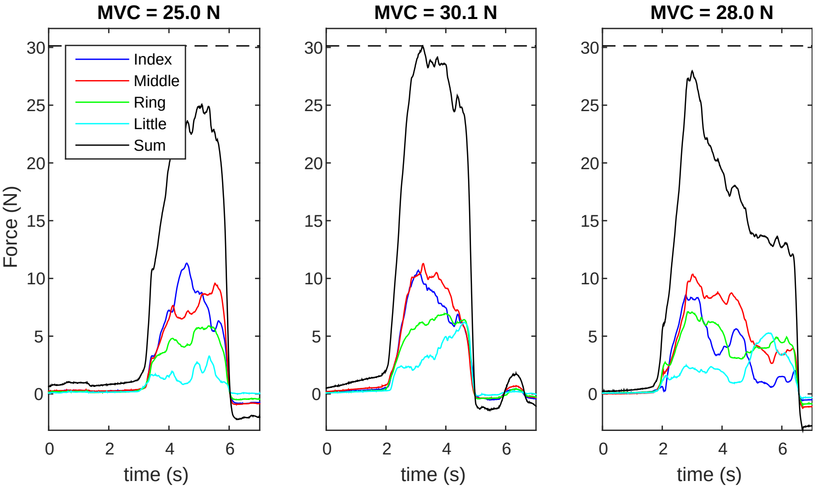


EXPERIMENT - RESULTS (JEBSEN-TAYLOR)

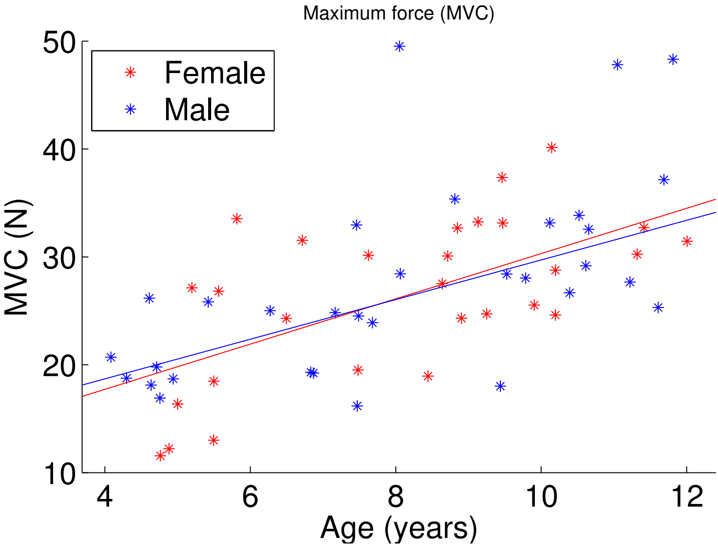


Experiment - results (MVC)

- The subjects were requested to press as hard as they could with all four fingers between 2 beeps (5 seconds apart)
- The maximum force from 3 repetitions was selected

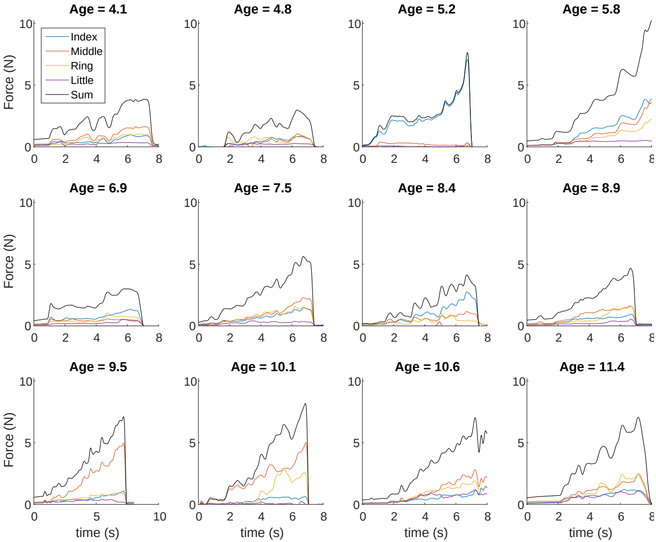


EXPERIMENT - RESULTS (MVC)



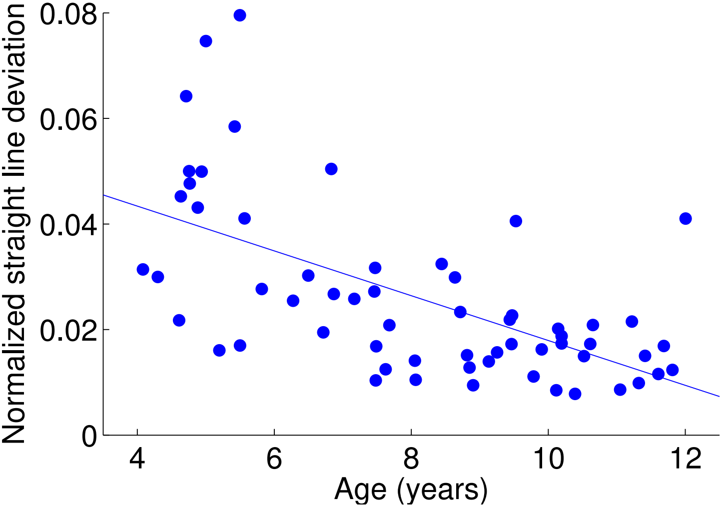
EXPERIMENT - RESULTS

The children were able to perform the task (more or less)



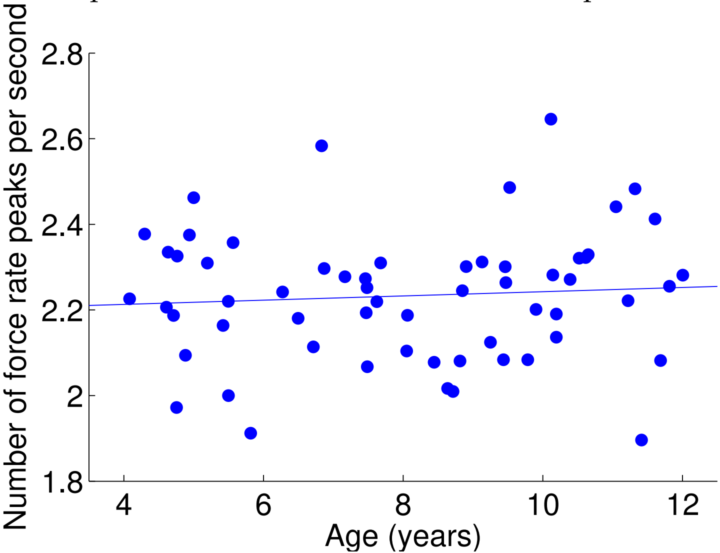
EXPERIMENT - RESULTS

There was an improvement in performance with age



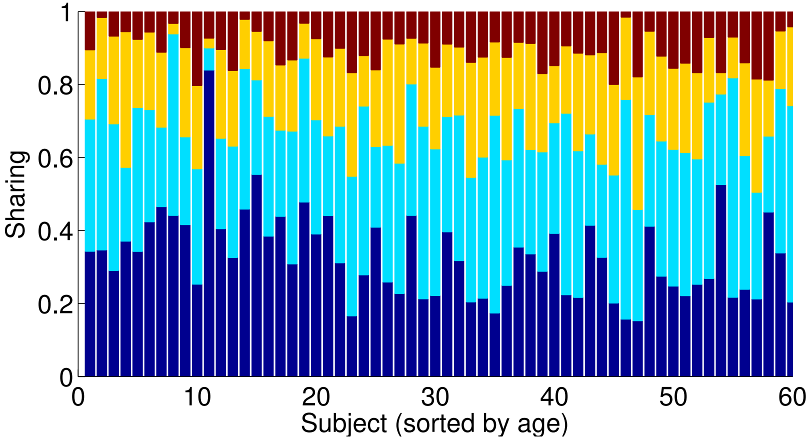
Experiment - results

This improvement is *not* due to less force rate peaks



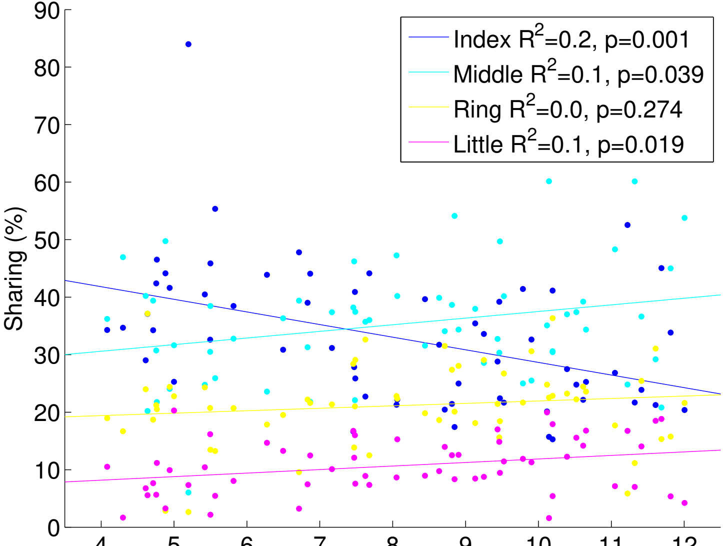
Experiment - results (Finger sharing)

The index and middle fingers did most of the work

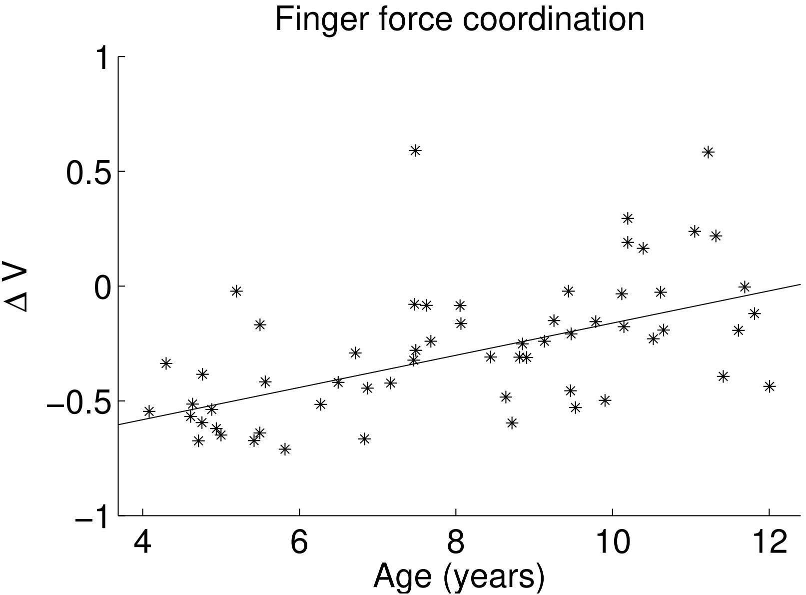


Experiment - results (Finger sharing)

The sharing became more equal with age

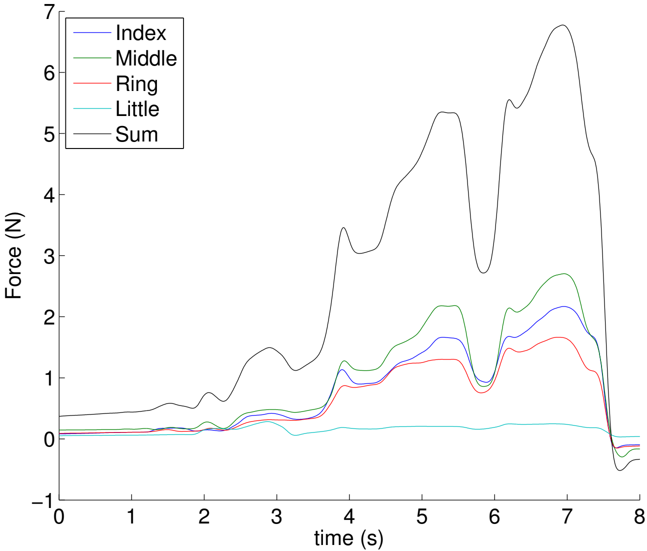


Experiment - results (Mean Delta V)



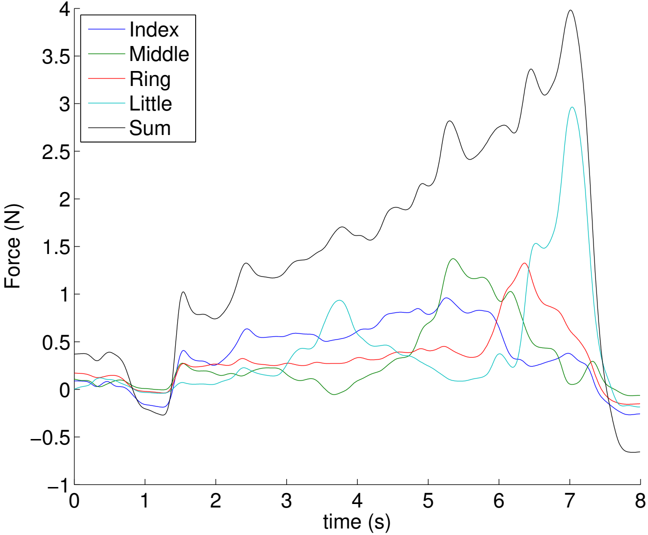
Experiment - results (example - low)

Lowest $\Delta V = -0.7$. Example of the "fork" strategy

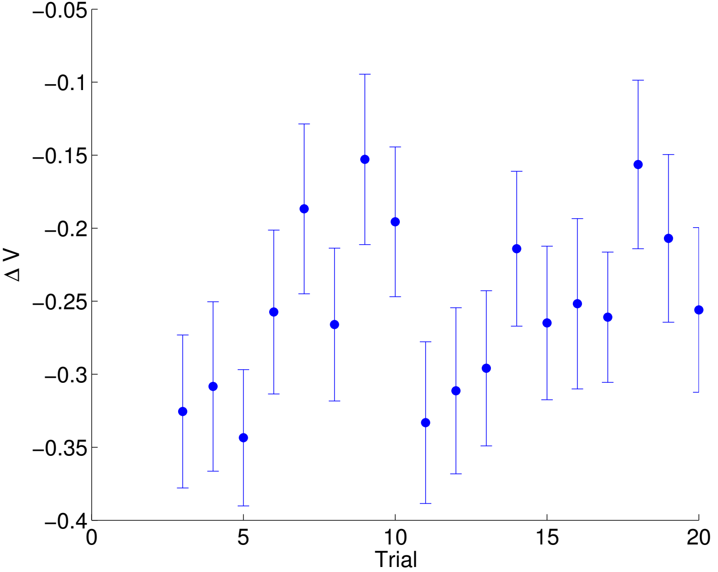


Experiment - results (example - high)

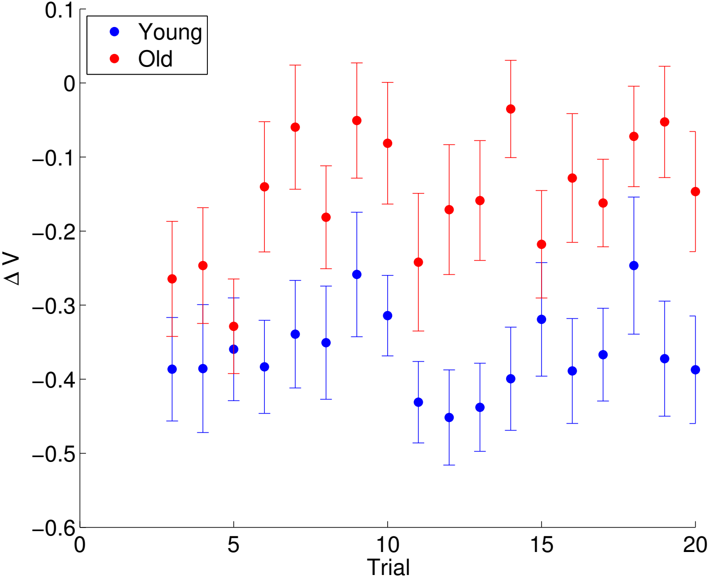
Highest $\Delta V = 0.59$. Independence of the fingers



Experiment - Is there learning?



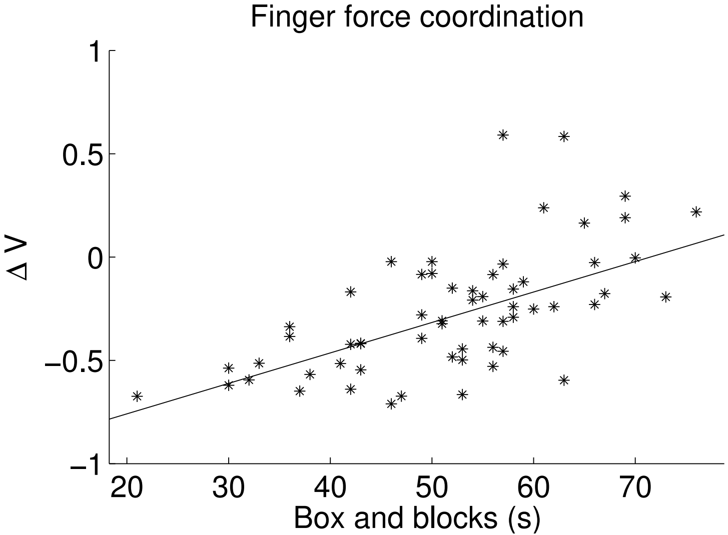
Experiment - Is there learning?



WHAT PREDICTS ΔV?

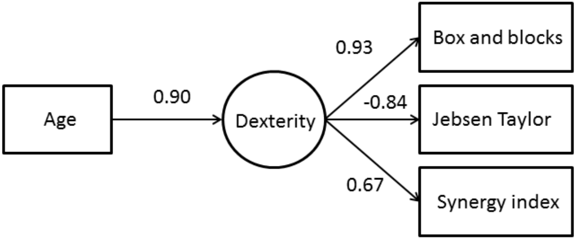
- We observed that there is a significant correlation between age and ΔV
- We tested if any of the behavioral measures could also predict ΔV
- The best correlation was found to be with the right hand box and blocks score ($R^2 = 0.39, p < 0.0001$)

WHAT PREDICTS ΔV?



WHAT PREDICTS ΔV?

- However, if we remove the effect of age, none of the predictors are significant
- This can be seen using SEM (structural equation modeling)



CONCLUSIONS

- When there are multiple effectors in a redundant task, we can use this redundancy to our advantage
- This is known as motor "abundance" (rather than the degrees of freedom problem)
- We can use this abundance to be more stable and flexible in performing the task

Conclusions

- In children aged 4 to 12, we observe an improvement with age in the ability to take advantage of this redundancy
- The best correlation is observed with right hand box and blocks performance, but not when controlled for age
- There does not seem to be a plateau in performance, further testing with older ages (e.g. 12-20) would help understand the development of this skill
- Repeated testing with the same subjects could also help understand the connection between force coordination and performance of functional tasks

Conclusions: next step

- We are now testing children with acquired and development brain injury to understand the connection between force coordination and performance of functional tasks
- Testing of older children would be a good complement to this study

THANK YOU

- Collaborators on this project: Dr. Sharon Shaklai and Dr. Aviva Bloch (Beit Loewenstein)
- Moran Levin - research assistant

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CrossMark

RESEARCH ARTICLE

Development of finger force coordination in children

Sharon Shaklai[1,2] · Aviva Mimouni-Bloch[2,3] · Moran Levin[4] · Jason Friedman[4,5]